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RELIABILITY EVALUATION OF LARGE SOLID ROCKET ENGINES
DURING ENGINEERING DEVELOPMENT

By

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Abstract

A method of evaluating reliability of large scale rocket engines during a Research and Development Program prior to missile flight tests is presented. Reliability estimates are obtained even though the configuration of the engine is undergoing change and the objectives of test firings vary. Each engine is apportioned into Principal Subsystems which are screened for their degree of representation of the final configuration. The intention of each test firing is determined prior to the test and the behavior of the Principal Subsystem when tested within the engine environment is classified according to pre-specified ground rules as a Success, Failure or Exclusion. These results are then statistically combined to give an estimate of engine reliability.

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Foreword

The concepts used and the approach taken to solve the particular problem discussed in this paper may be generalized to apply and be utilized for systems in which the following situations occur.

1) It is desired to evaluate the reliability of the system against its end use.
2) The system is in a state of continuous development towards an end configuration.
3) The intentions of the tests vary as the system evolves and there are nc or few tests specifically for reliability evaluation.
4) There is a limited number of systems available for testing and/or there is a limited number of times (perhaps only once) that a system can be tested.

For large solid rocket engines, each of these situations occur. The specific details of the proposed solutions are presented after the practical and statistical problems are discussed. It should be noted that this paper specifies how the reliability of the system can be evaluated; it does not discuss how reliability may be improved.

Objectives and Problems

The objectives are to define and measure during a research and development program characteristics which are indicative of the engines ability to reliably perform its function of propelling a missile of one or more stages into a certain target area. To accomplish these objectives three major practical and statistical problems must first be considered:

a. Relating engine reliability requirements in an R and D program to the weapon system's operational reliability requirements.
b. Obtaining valid reliability data in an R and D program when the objectives of the tests vary and the configuration of the engine undergoes continous modification.
c. Making efficient reliability estimates based upon the results of a limited number of full-scale engine test firings.

Discussion of Problems

a. The ultimate intention for a given missile is that it will fall within a certain target area. This intention can be projected into single-stage engine reliability requirements as implying that for successful operation

of the missile there should be no catastrophic failure which would result in mission abort nor any unsatisfactory performance which would result in a significant target miss. On the other hand, operation of a given engine which exhibits no catastrophic failure, and for which the performance parameters all lie within specified limits, would, assuming successful operation of the remainder of the missile, produce a scatter of hits in and around the target area. The ground rules which interpret the success or failure criteria of the weapon system into the success or failure criteria of the engine may, to a certain extent, be based on engineering and arbitrary judgments. However, providing the ground rules are clearly stated, understood, and rigorously applied, reliability estimates can be made which are valid within the framework of those ground rules. Furthermore, only developmental test stand firings can be utilized for reliability evaluation during the program, since flight tests will not yet have been conducted. Thus, the effect of performance interactions of an engine with the remainder of the systems in the missile cannot be comprehensively known during this period. Therefore, if reliability is defined as the probability of a successful operation of the weapon system, then the reliability of the engine, as a functioning subsystem of that weapon system can be interpreted as the probability of successful operation of the engine. This in turn can be regarded as the probability of performing within engine specifications. Thus, the relationship between the weapon system and engine is defined by the specifications.

The numerical value of reliability which the engine may be expected to display or contractually demonstrate would depend on the "state of the art" of the engine, the number of units available for testing, and the reliability requirement of the weapon system.

b. The applicability of engineering development tests for reliability evaluation is dependent on the validity of the data and the intention and circumstances of the tests generating the data. Generally, the nature of developmental testing differs from reliability testing. Reliability testing would usually involve a large homogeneous sample of engines representative of the final configuration. It is generally not practical to produce a large number of expensive engines specifically to demonstrate the system's reliability. Even if this were done, by the time production and testing were

completed the reliability results would refer to an obsolescent configuration, since simultaneous engineering testing would probably have resulted in further design improvements. Consequently, in this program reliability must be estimated from the results of R and D engineering tests. However, engineering testing is usually performed with small sample sizes on changing configurations. Therefore, it is necessary to take into account the objectives of an engineering test, to ascertain how these objectives differ from those of a reliability test and to see if it is possible to reconcile the two. This must be done without restricting the exploratory nature of development testing.

This is accomplished by "screening" the engineering tests for reliability use by means of the "Declaration Policy" and determining the degree of representation of the engine towards its flight configuration. Thus, even though the item is evolving during the R and D test period, representative data can be obtained and used to determine a valid estimate of reliability.

c. The foregoing discussion implies that only full-scale engine tests will be used for reliability evaluation. A development program for state-of-the-art solid propellant engines involves a great deal of experimental testing with subscale engines. Initial feasibility studies for new or modified propellant formulations are best and most economically undertaken in small and subscale engines in order to provide evidence that the propellant will satisfy internal ballistic requirements in the full-scale engines. In many instances, accurate scaling predictions of internal ballistic performance can be established. Further testing with subscale engines is undertaken in order to determine properties of charge and case designs, insulation materials, movable nozzle designs, etc. for the full-scale engine.

However, there exist differences between subscale and full-scale engines which cannot be completely resolved by the use of scaling or correlation factors. For example, these differences might be due to the lack of sufficient knowledge of the mechanical properties of scaled-up propellant charges, such as of stress magnitudes and patterns, which are intimately related to problems of propellant cracking and propellant-liner separation.

Thus, while the engineering information obtained from subscale engine tests is essential for the development of performance and reliability of the full-scale engine, the best evidence to ascertain that the end product requirements will be met is obtainable only from tests of full-scale engines sufficiently representative of final design configuration.

Since there are only a limited number of full-scale engines representative of final configuration available for testing, the statistical method of making reliability evaluations becomes of great importance. The statistical technique, introduced in this program, supersedes "the product rule" method by allowing more efficient confidence limits to be estimated.

Description and Conduct of the Program

The program is divided into four parts:

a. A method of system apportionment.

b. A method of classifying R and D test results for reliability evaluation.

c. A declaration policy.

d. A new technique of estimating reliability.

System Apportionment

To compensate for the relatively small number of tests of full-scale engines, it is essential that all representative data be utilized. This is done by apportioning the engine into three Principal Subsystems, and each engine test is evaluated in terms of the behavior of the Principal Subsystems. Thus, the fact that an engine is not fully representative of the final configuration in any one test will not prevent the evaluation of those Subsystems which are operating in a configuration or manner representative of flight status. The three Principal Subsystems are:

a. The Propellant Charge-Ignition Subsystem.

b. The Case-Liner-Internal Insulation Subsystem.

c. The Thrust Vector Control Subsystem.

Engine reliability estimates are made from the Principal Subsystem test results (tested within the environment of the full-scale engine) and can begin with the first test firing.

Applicability of Principal Subsystem

The Principal Subsystems tested in a full-scale engine firing will be classified as applicable or inapplicable for purposes of reliability evaluation. In order to determine which of the Subsystems being tested in any full-scale test firing are sufficiently representative of flight configuration to be useful for reliability

evaluation, it is necessary to set up criteria which determine the Subsystem's applicability.

Principal Subsystem	Required Characteristics for Applicability
Subsystem A Propellant Charge-Ignition	W_p = propellant charge weight lies within $\pm 1\%$ of model specification limits
Subsystem B Case-Liner-Internal Insulation	1) Engine configuration includes flight-weight case and end closure as specified by current weight and balance status report. 2) Propellant weight as specified for Subsystem A
Subsystem C Thrust Vector Control	1) Engine configuration includes flight-weight movable nozzles. 2) Flight-weight APS actuator subassembly. 3) Propellant weight as specified for Subsystem A 4) Nozzles must be intended to actuate during test firing. 5) Predicted action time not less than model specification limit unless thrust termination operation is being tested.

Test Result Classification

Those tests which are applicable will be evaluated and categorized as Exclusion, Failure or Success. A result may be excluded prior to this test, the circumstances which permit this are listed below:

	All Principal Subsystems (A, B, C)
PRETEST EXCLUSION (Subject to approval of Prime Contractor/Program Manager)	1) The Principal Subsystem does not have required characteristics for applicability. 2) Due to the intention or circumstances of the test, a particular Subsystem may be excluded due to stated uncertain characteristics of operation relating to performance and/or possibility of malfunction; e.g., if inspection shows propellant voids or cracks of a sufficient degree so that malfunction would be expected; then the Propellant Charge-Ignition Subsystem may be considered for exclusion. 3) If internal ballistic performance is predicted to be outside current Model Specification limits, but the test firing is approved, then performance will be excluded. A maximum of two exclusions under this ground rule prior to the formal PFRT test program is allowable. No exclusions under this ground rule are allowable during the formal PFRT program. 4) Provisional Exclusion: A Subsystem will be excluded if there is a failure of an experimental part which has been so listed on the Declaration Form prior to the test, and which is being tested for the first time in a full-scale engine. However, if the Subsystem fails due to the failure of a nonlisted part, it will be classified as a failure. 5) Provisional Exclusion: A Subsystem will be excluded if there is a failure of an obsolete part which has been so listed on the Declaration Form prior to the Test. An obsolete part is defined as a part used in a test configuration for reasons of expediency, but for which there already exists a Reliability Design Change* for that part.

* A Reliability Design Change is defined as a modification to correct a previously observed failure, and must be intended to appear on all subsequent engines.

NOTE: Reasons for all exclusions must appear on the Declaration Form prior to the tests.

Each Principal Subsystem will be classified as having succeeded or failed depending on whether its performance in operational use would have resulted in a successful or failing flight. The exception to this would occur when for causes external to the Subsystem, the Subsystem was not given the opportunity to succeed or fail. The detailed ground rules are given below:

	Propellant Charge-Ignition Subsystem (A)
SUCCESS	1) The Subsystem does not fail and is not excluded; and performance is within the current Model Specification limits. 2) It operates without failure with performance outside current Model Specification limits, provided that this intention is so stated on the Declaration Form, and approved, prior to test. (See limitation above)
FAILURE	1) The igniter fails to operate or fails to ignite the propellant. 2) The ignition delay is greater than the maximum values specified by the current Model Specification limits. 3) The ignition peak pressure/thrust is greater than the equilibrium chamber pressure/thrust. 4) Rough combustion; i.e., chamber pressure/ thrust peaks $\geq 10\%$ of equilibrium chamber pressure/thrust. 5) Engine blow-up attributable to propellant or igniter. 6) The performance values lie outside the current Model Specification limits when the performances were declared to be within the current Model Specification limits.
POST-TEST EXCLUSION	1) Tests which fail due to causes external to Subsystem A; e.g., other Principal Subsystem failures, test operator error, instrumentation or facility malfunction, provided that failure of Subsystem A had not already occurred. 2) Failure of the Subsystem due to the failure of an obsolete or experimental part so listed prior to the test on the Declaration Form. 3) Tests in which Subsystem A did not fail but did not have the opportunity to satisfy the declared intention of the test.

Ground Rules for Classification of Test Results (Cont'd)

	Case-Liner-Internal Insulation Subsystem (B)
SUCCESS	1) The Subsystem does not fail and is not excluded.
FAILURE	1) Case or end-closure burn-through during normal operation.
POST-TEST EXCLUSION	1) Tests which fail due to causes external to Subsystem B; e.g., other Principal Subsystem failures, test operator error, instrumentation or facility malfunction, provided that failure of Subsystem B had not already occurred. 2) Failure of the Subsystem due to the failure of an obsolete or experimental part so listed prior to the test on the Declaration Form. 3) Tests in which Subsystem B did not fail but did not have the opportunity to satisfy the declared intention of the test.

	Thrust Vector Control Subsystem (C)
SUCCESS	1) The Subsystem does not fail, is not excluded and performs as programmed for the duration of the test.
FAILURE	1) Movable nozzles stick, jam, or do not deflect as programmed. 2) Gas leakage or burn-through in any part of the movable nozzle assembly occurs. 3) Nozzles under- or over-travel intended deflection > 0.5 degrees. 4) APS does not deliver rated power or malfunctions. 5) Actuators malfunction.
POST-TEST EXCLUSION	1) Tests which fail due to causes external to Subsystem C; e.g., other Principal Subsystem failures, test operator error, instrumentation or facility malfunction, provided that failure of Subsystem C has not already occurred. 2) Failure of the Subsystem due to the failure of an obsolete or experimental part so listed prior to the test on the Declaration Form. 3) Tests in which Subsystem C did not fail but did not have the opportunity to satisfy the declared intention of the test.

NOTES: It may be required that the engine contractor be held responsible for attaining a numerical reliability requirement. This implies that the numerical reliability requirement should not encompass: (1) equipment developed by another associate contractor which is tested in conjunction with the engine contractor's system; nor (2) interface attachments, the function of which is a joint responsibility between two or more associate contractors. When, however, equipment is furnished by vendor or subcontractor to the engine contractor, and does not fall in category (2), the equipment is considered to be the engine contractor's responsibility with respect to meeting any numerical reliability requirements.

Declaration Policy

In order to establish the integrity of the data, it is necessary to determine the intentions of a test and by applying the ground rules for applicability establish the utility of the test results for reliability purpose. This is done by means of the Declaration Form which must be completed prior to each full-scale test as part of the Test Plan. It is then submitted to the program manager for approval. The form is self-explanatory, but it is appropriate to note that when exclusions are declared the reasons should be given, together with any substantiating information and/or references to failure reports, inspection reports, engineering change orders, etc. For example, if a part is provisionally excluded by reasons of obsolescence, the engineering change order number or the new part (drawing) number, etc., should be given on the form. (Figure 1 is a sample Declaration Form.) The Program Manager might establish a limit to the number of provisional exclusions.

Reliability Reporting and Estimation

The Reliability Report Form (Figure 2 is a sample Reliability Report Form) is completed as soon as possible after the test data is reduced. The data are then evaluated by the contractor's reliability group on the basis of the ground rules and the information contained on the Declaration Form. This is done for each Principal Subsystem after each full-scale test. A short description of the failure, or reason for exclusion when any Principal Subsystem is so classified, should appear in the remarks column. When a failure occurs which cannot be assigned to any particular subsystem, this fact should be noted as well. References to failure, and corrective action reports, etc., should also be given as necessary. The Reliability Report Forms covering a particular calendar month can then be gathered in chronological order and summarized as illustrated in the example to follow. The best estimate and 95% lower confidence limit of reliability can then be obtained by the methods given later and reported monthly.

Representative and Current Data

Because of the small number of tests available for evaluation, each Principal Subsystem must necessarily display a relatively high reliability, and few failures must, therefore, occur. However, at the beginning of the program several failures may occur, establishing such a high cumulative failure rate that, were there no provision for discarding data, an exorbitantly large number of successful tests would

be needed before the earlier failure rate would be "absorbed." This is not feasible, and in a development program which expects to improve the product, it is not realistic to handle the data this way. If these failures were random failures or failures due to unassignable causes, then it would not be legitimate to discard the earlier data, as this failure pattern would be the manifestation of the inherent reliability and, as such, would indicate that the Subsystem was not sufficiently reliable. However, the earlier failures are not generally random; i.e., they do have assignable causes, and in a development program are subject to analysis and corrective action.

This corrective action is called a Reliability Design Change, which is defined as a modification to correct a previously observed failure and must be intended to appear on all subsequent engines. Data generated after the Reliability Design Change will be regarded as homogeneous, and earlier data discarded as being no longer representative of the current design. Data produced after the Reliability Design Change will be called Current Data. The decision as to what constitutes a Reliability Design Change is subject to the approval of the Program Manager and relates only to that particular Subsystem for which corrective action has been taken.

All engine reliability estimates (as described in the example below) will be based on Current Data only. Thus, when counting applicable tests the count should not be extended any further back than the last Reliability Design Change for each Principal Subsystem.

Performance Reproducibility

Performance reproducibility is not incorporated into the Reliability evaluation method described in this paper; i. e., it is not incorporated into the reliability estimates to be reported. However, generally, Model Specifications contain requirements relating to between engines performance variation. Applicable data obtained from the Reliability Report Form would be used to determine the probability of meeting these variability requirements. Further, if these pertinent performance parameters are suitably chosen; e.g., specific impulse, thrust, weight, etc., the probability of the missile falling within the C.E.P. can be computed on a propulsion reliability basis.

Engine Reliability Estimation

Technique of Estimation*

Engine reliability will be computed from Principal Subsystem test results. After each test, it will generally be possible to classify each of the Principal Subsystems as having succeeded, failed, or been excluded. The exception to this classification can occur when there is a failure but it is not known which Principal Subsystem(s) failed. While it is desirable to be able to classify completely each test, an unassignable failure still represents a system failure and must be incorporated into any system reliability estimate. The general procedure is as follows: The number of applicable tests on each Principal Subsystem are determined. The minimum of these three numbers, N, gives the number of equivalent engine tests performed. To compute the reliability for the engine it is necessary to count the number of known failures which occurred in the last N tests of each Subsystem. In addition, those failures which have not been assigned or attributed to any Subsystem in particular are arbitrarily assigned to the individual Principal Subsystems. This is done for all possible arrangements consistent with the number of failures and tests appearing in the unassignable category. Thus, when the known failures are added to the arrangements, a set of all possible failure arrangements for a given number of equivalent engine tests is obtained. Any one failure arrangement can be written $(N; f_1, f_2, f_3)$, where f_1, f_2, f_3 are the number of failures of the separate Subsystems; and $f_1 + f_2 + f_3$ is therefore the total number of assignable and unassignable failures during the period of N equivalent engine tests. The minimum reliability for 95 percent confidence can then be obtained from the tables or graph for each $(N; f_1, f_2, f_3)$. Some of the numerical values of these reliabilities will be the same since the value of the reliability is independent of the order of f_1, f_2 and f_3.

The smallest of the reliabilities is taken as the minimum demonstrated reliability which could occur in a population represented by the sample. If later analysis permits unassignable failures to be allocated, the estimates will then be recomputed.

The best estimate of reliability for the same sample, is obtained by taking that combination of failures which gave the smallest of the reliabilities for the confidence estimate and substituting in $(N - f_1)(N - f_2)(N - f_3)/N^3$.

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* The mathematical basis for the method of reliability estimation is based upon the work described in References (1) and (2) and the tables in Reference (3).

An Example of Estimation

a. An example will illustrate the method of engine reliability estimation. The method of tabulating the results as shown in the table below will be found convenient. During each test all Principal Subsystems are physically present but may or may not be applicable for reliability evaluation according to the ground rules. The result of the test for each of Subsystems A, B, and C will be success (S), failure (F) or exclusion (which is indicated by a blank in the table). In addition, there may be unassignable failures. These are indicated under that combination of Subsystems (AB, BC, CA or ABC) which contains the potential failing Subsystem(s). The following table of hypothetical results, together with accompanying detailed explanation, will clarify the above discussion.

Test No. (Chronological)	Reliability Report No.	Date of Test	Assignable Results			Unassignable Failures			
			A	B	C	AB	BC	CA	ABC
1			S						
2				F					
3			S		S*				
4						F			
5			S*	S*	F*				
6			S*				F*		
7			S*	S*	S*				
8									F*
9			S*	S*					

Subsystem	No. of Times Tested	Assignable Failures	Possible Failures
A	8	0	2
B	7	1	3
C	5	1	2

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* See paragraph b, following page.

Test No.	Explanation of Tabulation
1	Subsystem A was applicable and a success. B, C were excluded.
2	Subsystem B was applicable and a failure. A, C were excluded.
3	Subsystems A and C were applicable and successes. B was excluded.
4	Subsystems A and B were both applicable but a failure occurred; post-test analysis failed to establish which of the two Subsystems failed or whether it was both. C was excluded.
5	A, B were both successful; C a failure.
6	A was a success but an unassignable failure occurred in B and/or C.
7	All Subsystems successful.
8	All Subsystems applicable but (an) unassignable failure(s) occurred in one or more of them.
9	A and B were both successful. C was excluded.

b. In the above example, the Principal Subsystem experiencing the fewest number of tests is C with 5; thus, a maximum of the equivalent of 5 complete engines have been tested. Counting back from Test No. 9 for the last 5 tests of each Principal Subsystem, it is found that A was present and applicable in Tests No. 9, 8, 7, 6, 5; Subsystem B in Tests No. 9, 8, 7, 6, 5 and Subsystem C in Tests No. 8, 7, 6, 5 and 3. Thus, only the results of the aforementioned tests for each Subsystem should be utilized in obtaining the engine reliability estimate, i.e., only those results marked by an asterisk in the table. During the period of testing the 5 engines, A has no known failures and 1 possible failure in Test No. 8. B has no known failures, 2 possible failures (one in Test No. 6 and one in Test No. 8). C has one known failure in Test No. 5 and 2 possible failures in Tests No. 6 and 8. All the possible arrangements of the unassignable failures are shown below.

Subsystem A	Subsystem B	Subsystem C	Total Unassignable Failures
0	0	2	2
0	1	1	2
0	2	0	2
1	0	1	2
1	1	0	2

The known failures: 0, 0, 1, respectively, are added to each of the above arrangements to give all possible variations, both known and unassignable; in the notation $(N;\ f_1,\ f_2,\ f_3)$ these become

$$(5;\ 0,\ 0,\ 3)$$
$$(5;\ 0,\ 1,\ 2)$$
$$(5;\ 0,\ 2,\ 1)$$
$$(5;\ 1,\ 0,\ 2)$$
$$(5;\ 1,\ 1,\ 1)$$

From Figure 3 it is seen that the first combination gives a value of 7.6 per cent for minimum demonstrated reliability at the 95 per cent confidence level. The next three combinations give 16.3 per cent and the last combination gives 18.9 per cent.

The minimum of the possible reliabilities, i.e., 7.6 per cent with 95 per cent confidence is the reported reliability. In this example, based on hypothetical test results, the possible reliabilities vary considerably because of two facts. Firstly, there is a much greater proportion of unassignable failures than known failures and, therefore, the arrangements greatly affect the reliability estimates, and secondly, the sample size is very small. Generally, this will not be the case, so that the reliability estimates will be much closer together.

The best estimate of reliability, as obtained from the worst combination of failures (0, 0, 3), given by the formula is

$$(5 - 0)\ (5 - 0)\ (5 - 3)/5^3 = 2/5 \ = 40\%$$

Use of Figures 3 and Table I

Figure 3 gives the estimate of reliability at a 95 per cent confidence level for a given number of trials, $N = 5$ to 40, and a particular combination of failures $(f_1,\ f_2,\ f_3)$. The figure covers values of $(f_1 + f_2 + f_3)$ from 0 to 20; however, not

all failure combinations are plotted. Table I lists in descending order with respect to the reliability values, various failure combinations. Only those combinations marked with a single asterisk have been plotted. Thus, if it is necessary to obtain a reliability estimate for a combination not plotted, e.g., (3, 3, 1), it can be done for any particular N by interpolating between the curves for (3, 2, 2) and (4, 2, 1). Reference 3 allows reliability estimates to be obtained for a wider range of N and various confidence levels.

Conclusion

The paper has shown how the reliability of an engine can be estimated from engineering development tests without restricting the exploratory nature of the tests. These estimates can be obtained even though the configuration and/or hardware being evaluated has not reached its final design. The statistical technique used in the analsysis of the data results in a more efficient confidence estimate and thereby supersedes the product rule for interval estimation.

References

(1) R. J. Buehler, "Confidence Limits for the Product of Two Binomial Parameters", J. Amer. Stat. Assoc., 52, pp. 482-493, (1957)

Ref- (2) STL Report No. GM-TR-0165-00506, "Measurement of Over-All System Reliability Utilizing Results of Independent Subsystem Tests", October 1958.

(3) STL Report No. TR-59-0000-00756, "Tabels of Upper Confidence Limits on Failure Probability of 1, 2 and 3 Component Serial Systems", (Two Volumes) July 1959.

DECLARATION FORM

A. Engine Serial No.__________ Engine Type__________ Test Stand__________

Test No.__________ Date of Test__________

B. Which of the following Principal Subsystems are applicable for reliability evaluation?

	Applicable	Not Applicable
(1) Propellant Charge-Ignition (A)	☐	☐
(2) Case-Liner-Internal Insulation (B)	☐	☐
(3) Thrust Vector (C)	☐	☐

C. If any of the Principal Subsystems are not applicable state reasons.

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____

____

D. Which performance parameters should be excluded from reliability evaluation? State reasons: __________

____

____

E. Which components or parts are declared experimental or obsolete (for provisional exclusion)?__________

____

____

F. Comments:__________

____

____

G. Movable Nozzle Program: Number of cycles, angles of deflection, and period of operation __________

____

Signatures and Approvals:

Program Management __________ Test Engineer__________

Date__________ Reliability__________

FIGURE 1

RELIABILITY REPORT FORM

Date of Test ______ Test No. ______ Test Stand ______ Test Report No. ______

Engine Type ______ Engine Serial No. ______

Engine Test Data			
Total Impulse, lbf-sec	______	Ignition Delay, sec.	______
Average Thrust, lbf	______	Ignition Peak Thrust, lbf	______
Specific Impulse, lbf sec/lbm	______	Useful Propellant Weight, lbm	______
Max-Min (Thrust Time Curve), lbf	______	Engine Weight, lbm	______
Rate of Thrust Rise, lbf/sec	______	Propellant Mass Fraction	______
Rate of Thrust Decline	______	Firing Temperature, ^{o}F	______
Action Time, sec	______	Other Environments	______
Average Chamber Pressure, psia	______		

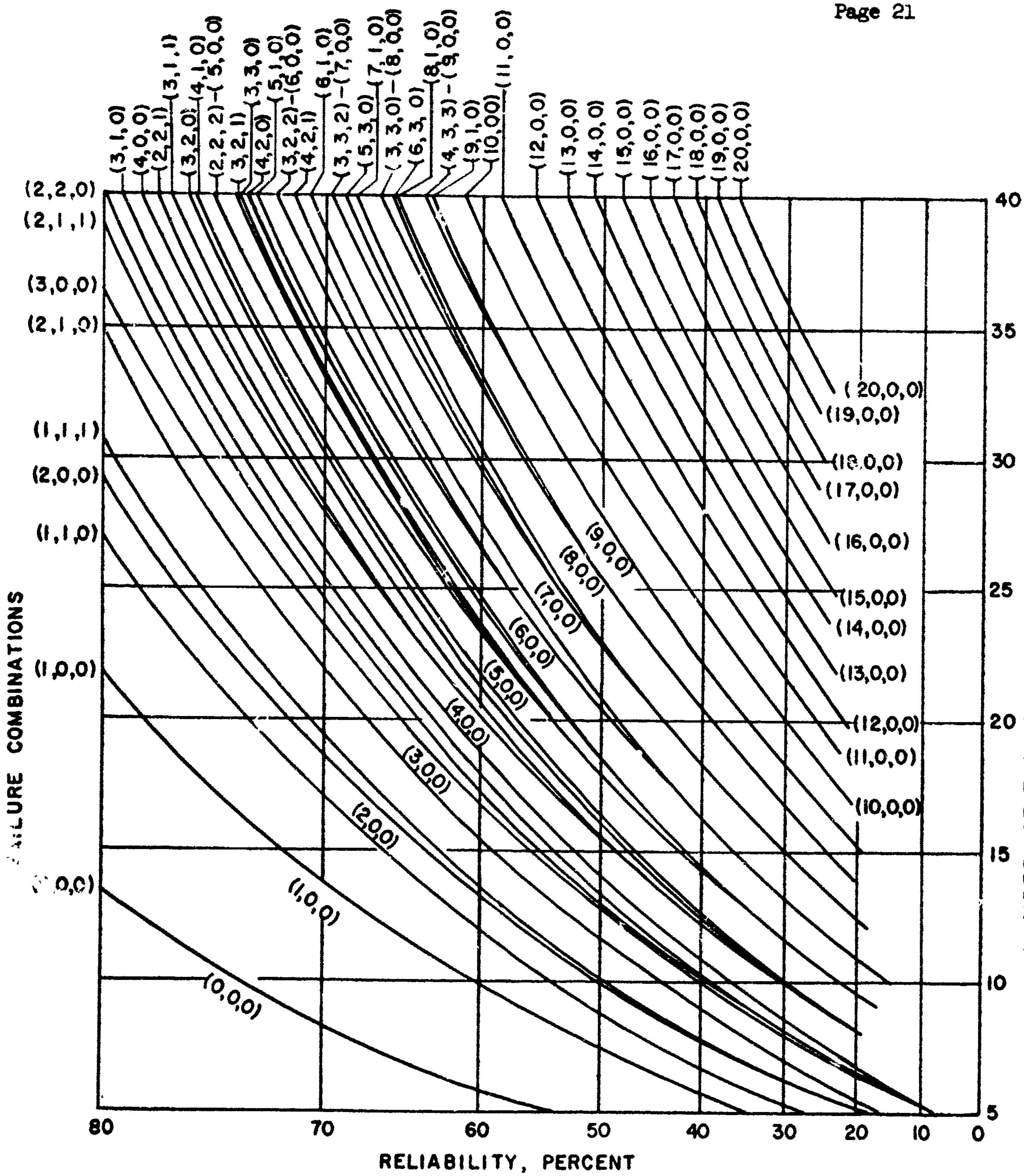
Test Result Classification
(to be completed by reliability group)

Principal Subsystem	Exclusion Pre-test	Exclusion Post-test	Failure Perf Excl	Failure Perf Not Excl	Success Perf Excl	Success No Perf Fail	Remarks
A							
B							
C							

Additional Remarks: ______

Responsible Engineer ______ Department and Group ______ Date ______

Figure 2



95 PER CENT LOWER CONFIDENCE LIMIT TO TRUE RELIABILITY FOR OBSERVED FAILURE COMBINATIONS OF A THREE-SUBSYSTEM SERIAL SYSTEM WITH N($5 \leq N \leq 40$) TRAILS PER SUBSYSTEM

(ALL PERMUTATIONS OF FAILURE COMBINATIONS (f_1, f_2, f_3) ARE EQUIVALENT.)

FIGURE 3

Table 1 List of Failure Combinations in Order of Descending Reliability

Total No. of Failures ($f_1+f_2+f_3$)	Combination of Failures (f_1, f_2, f_3)			Total No. of Failures ($f_1+f_2+f_3$)	Combination of Failures (f_1, f_2, f_3)			Total No. of Failures ($f_1+f_2+f_3$)	Combination of Failures (f_1, f_2, f_3)		
0	0	0	0*	8	3	3	2*	11**	10	0	0*
					4	2	2				
1	1	0	0*		4	3	1	12**	11	0	0*
					4	4	0				
2	1	1	0*		5	2	1	13**	12	0	0*
	2	0	0*		5	3	0*				
					6	1	1	14**	13	0	0*
3	1	1	1*		6	2	0				
	2	1	0*		7	1	0*	15**	14	0	0*
	3	0	0*		8	0	0*				
								16**	15	0	0*
4	2	1	1*	9	3	3	3*				
	2	2	0*		4	3	2	17**	16	0	0*
	3	1	0*		4	4	1				
	4	0	0*		5	2	2	18**	17	0	0*
					5	3	1				
5	2	2	1*		5	4	0	19**	18	0	0*
	3	1	1*		6	2	1				
	3	2	1*		6	3	0*	20**	19	0	0*
	4	1	0*		7	1	1				
	5	0	0*		7	2	0	21**	20	0	0*
					8	1	0*				
6	2	2	2*		9	0	0*				
	3	2	1*								
	3	3	0	10	4	3	3*				
	4	1	1		4	4	2				
	4	2	0*		5	3	2				
	5	1	0*		5	4	1				
	6	0	0*		5	5	0				
					6	2	2				
7	3	2	2*		6	3	1				
	3	3	1		6	4	0				
	4	2	1*		7	2	1				
	4	3	0		7	3	0				
	5	1	1		8	1	1				
	5	2	0		8	2	0				
	6	1	0*		9	1	0*				
	7	0	0*		10	0	0*				

NOTE:

All permutations of f_1, f_2, f_3 are equivalent.

*Plotted in Figure 3.

**For those values of $f_1 + f_2 + f_3 \geq 11$ the estimate is obtained from $[N;\ (f_1 + f_2 + f_3 - 1),\ 0,\ 0]$ unless two of f_1, f_2, f_3 (f_2, f_3, say) are zero, in which case the reliability is given by $(N;\ f_1,\ 0,\ 0)$.